

FINAL TECHNICAL REPORT

"SPACE INFRARED TELESCOPE FACILITY PROJECT"

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SIRTF Final Report

Dale P. Cruikshank, Principal Investigator

This is a final report on a grant to the Principal Investigator to serve as a Planetary Science Consultant to the Science Working Group of the Space Infrared Telescope Facility (SIRTF) Project.

The functions of the PI during the grant period were:

1. To inform the planetary science community of the progress and status of the SIRTF Project.
2. To solicit input from the planetary science community on needs and requirements of planetary science in the use of SIRTF at such time that it becomes an operational facility.
3. To prepare a white paper on the use of SIRTF for solar system studies, and to present the results of the study to the SIRTF Science Working Group.

In pursuit of these objectives, the following activities were undertaken:

1. The PI presented a talk on SIRTF at the November 1986 meeting of the Division for Planetary Sciences (DPS) of the American Astronomical Society, the largest body of planetary scientists in the US. In addition, he organized a SIRTF and Planetary Science workshop held at the same DPS meeting in Paris to inform scientists in details of the project and to solicit their input to the white paper report.

At the November 1987 meeting of the DPS, a second workshop was conducted by the PI to inform the community of solar system scientists further on the status of the project.

The PI attended five meetings of the SIRTF Science Working Group as Planetary Science Consultant under this grant.

The PI published a newsletter for the planetary science community on the use of SIRTF for solar system studies, and distributed this newsletter to scientists with a particular interest in the project.

2. During the special DPS sessions noted above, the PI solicited input from the scientific community for the white paper. In addition, in March 1987, a special session for SIRTf studies of solar system bodies was held in Tucson, AZ in conjunction with another meeting on planetary atmospheres. The specific purpose of this session was to obtain input to the preparation of the white paper. The organization of the session was shared between the PI and Dr. Michael Mumma.

A large amount of correspondence was conducted by the PI with solar system scientists to obtain input for the white paper.

3. The white paper, entitled **SIRTf and Solar System Studies** has been completed, and is attached to this report as the major result of the study undertaken.

The essence of this white paper has been presented to the Science Working Group on two occasions, and in early March 1988 will be forwarded to Dr. Charles Felerin, NASA Headquarters.

SIRTF and Solar System Studies

Dale P. Cruikshank

I. INTRODUCTION

This is a report to the SIRTF Science Working Group on the use of SIRTF for studies of importance to planetary science. In the preparation of this report, no assumptions were made as to other possible Earth-orbiting infrared observatories studying planetary problems prior to the launch of SIRTF. Problems in planetary science noted herein are those that are current and important in 1988; it is essentially impossible to predict which of these problems will persist until the epoch of SIRTF in orbit, just as it is impossible to predict what new significant problems will arise between 1988 and 1996.

This report does not address details of the search for extra-solar planetary systems.

Low resolution spectroscopy (spectrophotometry) of solar system bodies is given particular attention in this report, and a recommendation concerning the wavelength region covered by the payload infrared spectrometer is made. In addition, the interest of the community of planetary scientists in high-resolution spectroscopy from earth orbit is addressed here, and a recommendation is made on behalf of that community for the inclusion of a high-resolution spectrometer on SIRTF. This recommendation is also noted in the forthcoming report of the Planetary Astronomy Committee (D. Morrison, Chair). The high-resolution spectrometer is considered in this report only in the context of planetary science, though such an instrument could be expected to have great power for many experiments in astrophysics.

II. THE SOLAR SYSTEM IN THE INFRARED

Modern planetary science shares with astrophysics an enormous debt to infrared technology. Many of the most important advances in the past two decades have come from the application of infrared observational techniques to planetary bodies by the use of ground-based and airborne telescopes and spacecraft sent to the planets for in situ measurements. Infrared spectroscopic observations of planetary atmospheres have given us fundamental information on the chemical compositions of those atmospheres, as well as their temperature-pressure structures over a wide range of altitude. For those solar system bodies without atmospheres, infrared observations have yielded basic information on their dimensions, surface thermophysical properties, and their reflectivities. The volcanic activity of Jupiter's satellite Io is monitored from Earth by infrared telescopic observations, and the dust comae of comets are probed by infrared observations from

the ground and from spacecraft. Every American space probe to another planet has carried at least one, and usually several, infrared instruments.

Solar system bodies reflect sunlight, and emit heat radiation according to their temperatures. Their temperatures depend upon their distances from the sun, their albedos, and the influences of atmospheres on those bodies that have them. The value of a cryogenic space telescope for observations of solar system bodies is twofold: first, observations of the thermal emission of faint planetary sources can be made without the dominating emission from the atmosphere and from the telescope; second, the absorbing properties of the earth's atmosphere are absent in space. The scientific rationale for the use of SIRT is focused on those investigations which require one or both of these principal attributes of a cryogenic telescope in space.

The reflected solar radiation and the thermal emission of the major planets are shown in Figure 1, while representative curves for the asteroids and comets at perihelion and the coldest of the solar system main bodies (Triton and Pluto) are shown in a later figure. The information content in both the thermal and reflected sunlight regions of the spectrum of a given body is very high. It includes the absorption and emission bands of gas species and the information they in turn carry on the temperature-pressure structure in planetary atmospheres; the integrated thermal budget of the body; and, for those bodies without atmospheres, the spectral signatures of such minerals and condensed volatiles that may occur on their surfaces. The information exists at many levels of spectral resolution; gas species and their isotopes are revealed at high spectral resolution (10^3 to 10^4), mineral and ice species are distinguishable at resolution 10^1 to 10^3 . Deconvolution of the temperature-pressure structures of planetary atmospheres from spectral bands requires spectral resolution 10^3 to 10^5 , depending upon the planet and the atmospheric constituents.

Comets and planetary coronae present phenomena fundamentally different from planetary surfaces and atmospheres, and the infrared spectral region offers opportunities to study the compositions and physics of these sources in some detail because of the information contained in their spectral emissions.

III. OBJECTIVES OF INFRARED STUDIES OF SOLAR SYSTEM BODIES

Even though ground-based astronomers have been studying the bodies in the solar system for centuries, and space probes have been sent to the planets for over 25 years, there are many remaining problems of great interest and physical significance in observational studies of planetary bodies, comets, satellites, asteroids, and other matter within the solar system. This section presents a framework for the definition of basic research problems that are amenable to observational study.

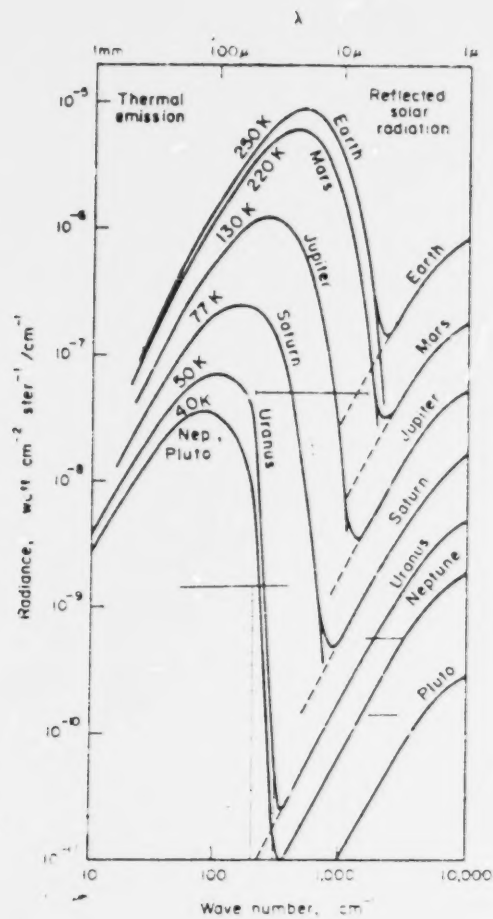


Figure 1. Thermal emission and reflected solar radiation of the -giant planets, 1 - 1000 μm . From Encrenaz.

A. Primordial Issues

A fundamental outstanding question concerns the initial complement of volatiles incorporated into the giant planets and their satellites during formation. Two extreme models are that the planets and satellites consisted of a) water, methane, ammonia (in order of decreasing abundance) or b) carbon monoxide, water, and molecular nitrogen. In the currently accepted model, the giant planets incorporated carbon monoxide, water, and nitrogen, while in the satellites water, methane, and ammonia dominated. Jupiter and Saturn might have converted carbon monoxide to methane and nitrogen to ammonia, but Uranus and Neptune might retain substantial amounts of carbon monoxide and nitrogen. The satellites of the outer planets might retain surface spectral signatures or the primordial partitioning of these constituents.

A related question concerns the incorporation of various volatiles into satellites and/or planetesimals in the outer solar system: were they incorporated at formation via clathrate hydrate condensates, pure solid condensates, or were they later acquired through impacts of volatile-rich comets? The surface ices of the small satellites of Saturn and the satellites of Uranus may show surface evidence of volatiles trapped in the water ice lattices. Radiation incident on the surface ices may have produced other species from the enclathrated molecules, and may have produced the patterns of albedo distribution observed on many of these objects.

A similar series of questions centers on three moon-sized outer solar system bodies that exhibit highly volatile surfaces/atmospheres. Specifically, what do the volatile complements on Titan, Triton, and Pluto/Charon imply for conditions in the regions of the solar nebula where they formed? For example, the origin of Titan's nitrogen is unclear (it could have come from photolysis or other heating of ammonia), and the relationship of carbon monoxide and carbon dioxide in the satellite's atmosphere requires elucidation. Triton offers similar questions on the abundances of methane and nitrogen and the possible existence of carbon monoxide. Pluto and its satellite may have histories related to Titan and Triton; a thorough inventory of the volatiles on the surfaces and in the atmospheres is a crucial factor in understanding these bodies.

Other questions intimately related to the primordial matter from which the planets formed concern the present abundances of helium and deuterium in the interiors and gaseous envelopes of the giant planets. While the helium abundances of three of the major outer planets have been determined, that of Neptune is presently unknown. The variability of the helium abundance in the upper atmospheres with seasons on the planets is of interest because of the seasonal extremes experienced by Uranus in particular, and to lesser degrees by Saturn and Neptune.

Deuterium is an isotope whose presence and abundance in the atmospheres of the planets is a key indicator of the composition of the material from which the planets were made. Both helium and deuterium in the atmospheres of the planets provide indices of the primordial abundances of these materials for comparison with their abundances in the interstellar medium, and eventually in other galaxies.

B. Evolution of Giant Planet Atmospheres and Satellites

The chemical evolution of the giant planet atmospheres (and their interiors) may have been greatly influenced by the incorporation of volatile-rich planetesimals. The minor constituents in those atmospheres may preserve some of the information on the original volatile content and the possible enhancement by the late influx of planetesimals. The inventory of minor constituents is also an index of the chemical evolution induced by planetary heating and by photolysis at the tops of the atmospheres. Without a complete inventory of the atmospheric constituents of the giant planets, this complex problem cannot be solved. The sensitivity of SIRT will allow a fairly complete inventory of gaseous constituents to be made.

The evolution of volatile material within satellites may have surface and atmospheric manifestations suitable to observational study. A specific question concerns the possible present-day exsolution of methane, ammonia, carbon monoxide, and nitrogen from the interiors of planetary satellites. The search for volatiles in addition to water must be made for the satellites of Jupiter, Saturn, and Uranus. Pluto should show photochemical products of the methane on its surface; spectroscopically active constituents in the surface ices should be detectable.

C. Seasonal Processes in Giant Planet Atmospheres and Satellites

The orbital and rotational geometries give rise to seasonal effects on the giant planets ranging from minimal (Jupiter) to profound (Uranus). The chemical, thermal, and structural responses to the changing seasons are unknown, but in principle hold the keys to a great amount of information on the nature of these bodies. The variation of methane and its photochemical products in the atmosphere of Uranus as the planet moves from polar solstice toward the equinox should give information on the global energy balance and the methane distribution as a function of latitude. Monitoring studies of Neptune as its seasons slowly change will give similar information and permit detailed comparisons with Uranus. Monitoring the ammonia abundance in the atmospheres of Uranus and Saturn will give information on the role of this constituent and its photochemical products.

Similarly, seasonal monitoring of the atmosphere of Titan and the surfaces of Triton and Pluto/Charon hold the potential

for a much deeper understanding of these volatile-rich bodies. Titan undergoes a seasonal cycle resulting from the obliquity of its axis to the orbit plane. Observations of the hydrocarbon distribution over a season will give some understanding of the range of photochemical processes with changes in the insolation and will yield a better model of the formation of higher hydrocarbons and their presumed accumulation in the lower atmosphere or on the surface. Particulate photochemical products in the atmosphere arise from processes of interest in the Earth's atmosphere; a better understanding of Titan cannot but help in modelling global effects of photochemical smog production on our own planet.

Triton undergoes extremes in seasonal changes because of Neptune's obliquity and the inclination of Triton's orbit to Neptune's equator. The result is a cycle that changes the subsolar latitude over an enormous range; at the present time the subsolar latitude is approaching an extreme of 52 degrees (it changes from 40 degrees to 52 degrees between the years 1980 and 2000). The transport of volatiles on the surface and in the atmosphere of Triton is of extreme interest in the study of this apparently dynamic planetary satellite. Voyager will get a detailed but fleeting look at Triton in 1989 and will thus provide a background of ground truth against which future observational studies can be interpreted.

As Pluto moves through perihelion (1989) and then back to larger solar distances, the atmosphere in equilibrium with its surface volatiles (methane, and perhaps other constituents) will change in volume, structure, and in composition. Observations over a long time base will be essential in understanding the behavior of this planet and its volatile-rich satellite. Observations in the late 1990's will be uniquely valuable in establishing the physical properties of Pluto and Charon and their atmospheres at epoch of minimum solar distance. All observations of these bodies in the next century will be referenced to data acquired near perihelion.

The seasonal cycles of the outer planets and satellites are all longer than SIRTf's five-year lifetime, but Titan, Triton, Neptune, Jupiter and Saturn all show well-documented atmospheric changes in less than five years. Pluto is near perihelion during the projected SIRTf mission timeframe, thus providing an opportunity for study when its volatile constituents are most active.

D. The Comets

Comets are a diverse population of bodies that condensed in a volatile-dominated environment. Some of them originated in the solar nebula, but some may have formed near other stars. Infrared techniques are well suited to the study of comets because of the wide range of phenomena associated with them. The non-thermal molecular band emission has important components in the infrared, the warm dust in the coma of a comet yields

information on its composition and particle size spectrum to IR techniques, and near-infrared data are used to probe the composition of the nucleus and the innermost coma.

The abundances of CO, CO₂, and CH₄ may be crucial indicators of the regions where comets formed in the pre-solar and pre-stellar nebulae. The heterogeneity of a cometary nucleus is demonstrated by the variability of its emissions of these and other volatiles (water, for example) on a time scale of minutes, hours, and days, as was observed for Comet Halley. This variability in emission translates to a chemical inhomogeneity on spatial scales of roughly 100 m, and demonstrates that the nucleus probably incorporated cometesimals formed in several different temperature-density regions of the pre-solar nebula. The great diversity among comets is just beginning to be recognized, and it now appears that the study of a large sample of comets will yield valuable information on the conditions in the pre-solar nebula, and perhaps pre-stellar nebulae in neighboring parts of the Galaxy.

Each year, a few "new" comets are discovered during their first pass through the inner solar system, and more than a dozen comets trapped in orbits with aphelia less than 40 AU make appearances near the inner planets. These populations provide excellent targets for studies of both pristine and "weathered" comets by SIRTf over the mission lifetime. SIRTf can follow the numerous short-period comets, such as Tempel II ($p = 5.28$ yr) and other possible CRAF mission target comets, over those portions of their orbits in which the activity ranges from minimum to maximum.

The isotopic composition of the comets, including deuterium, is a vital index of the composition of the nebular material from which they formed, but information on cometary isotopes is almost nonexistent. The ortho-para ratio in water in comets is yet another index of great potential value in deciphering the conditions in the pre-solar nebula, and may offer a criterion for the identification of comets from other stars. The ortho-para ratio was measured for the first time in comet P/Halley and again in comet Wilson.

The discovery of organic material in the nuclear dust of Comet Halley, together with the growing recognition of the wide distribution of organic matter throughout the solar system (and in interstellar/interplanetary matter) and the discovery of active organic synthesis on some planetary bodies, opens a new area of intense interest in solar system studies. Organic molecules in comets are not only of interest in connection with the origin and synthesis of life on this and other planets, but also relate solid bodies in the solar system to the interstellar medium.

E. The Asteroids

Once termed "vermin of the skies" by astronomers, the asteroids are now known to preserve information on the

composition and conditions in the inner parts of the solar nebula. They are a source of the meteorites, and together with the comets have profoundly affected the evolution of the terrestrial planets structurally and in terms of the origin and evolution of the atmospheres. Asteroid and comet impacts on the Earth appear to have had major effects on terrestrial ecosystems.

The detailed study of the compositions of the asteroids, their connections to the many types of meteorites, and their relationship to comets of various dynamical categories, are topics of considerable importance in planetary science. Compositional studies are best done in the infrared where the minerals and volatiles found in asteroids have their principal spectroscopic signatures. Extension of the ground-based work into the thermal infrared offers the possibility of understanding not only the volatile content and other compositional issues, but to open further studies into the surface and bulk thermophysical properties of bodies of diverse size, collisional history, and origin.

F. Interplanetary Matter

The emission of the sky (outside the atmosphere) at infrared wavelengths out to ~ 100 μm is dominated by thermal radiation from solar system dust, which is concentrated toward the ecliptic plane. IRAS found detailed structure in the distribution of this dust. While the bulk of the material probably arises from collisions among members of specific asteroid families, some of it is injected into the inner solar system by comets. Indeed, several periodic comets have long-enduring dust trails first seen in IRAS data. The dust appears to remain in the comet orbits long after the comet's activity has ceased. Measurements of the optical and physical properties of the asteroidal and cometary dust by infrared techniques will shed further light on the composition of these bodies and the means by which they have scattered their refractory components broadly through the solar system.

G. Detection of Extra-Solar Planetary Systems

Planetary science is currently undergoing a broadening of its definitions to include material in the immediate vicinity of other stars. This redefinition has been fostered by developments in astronomical technology that make it possible to observe aggregates of circumstellar dust and gas, and, in principle, solid bodies of planetary dimensions associated with nearby star.

Companions to other stars, whether they be brown dwarfs or bodies of planetary scale, might be detected by their dynamical effects, or by their thermal signatures in the infrared. Whether they are already formed or are still in the process of forming, planets circling other stars are faint objects compared with their parent stars. In some cases, they may lie in dusty interstellar clouds that obscure them at optical wavelengths. Infrared techniques offer the opportunity to penetrate the dusty

veils as well as achieve a more favorable ratio of fluxes of the planet to star. The thermal signature of a population of a few solid planetary bodies can be distinguished from that of a dust cloud or pre-planetary matter from observations over a range of wavelengths available to a telescope in space, even if the spatial resolution of the telescope is inadequate to distinguish the two. This area, which will be a very fruitful one for SIRTf studies, will be treated in greater detail in a separate report.

IV. SIRTf BASELINE SYSTEM DESCRIPTION AND CAPABILITIES

Following are the baseline capabilities of the SIRTf telescope facility and instrumentation. The suitability to specific kinds of planetary research are considered in terms of these capabilities.

A. The Telescope and Facility

- Orbit altitude - 900 km
- Orbital inclination - 28.5 degrees
- Facility lifetime - 5 years with 10 year goal
- Spectral range - 1.8 to 700 micrometers
- Aperture - 85 cm
- Field of view - 7 arcmin
- Sensitivity - Natural background limited, 2 to 200 micrometers
- Image quality - Diffraction limited over the full infrared field of view at >5 micrometers and over a reduced field of view at 2.5 - 5 micrometers
- Pointing accuracy/stability - 0.15 arcsec/0.15 arcsec (1 sigma)
- Tracking non-sidereal targets - Up to 0.21 arcsec/sec without degradation of performance
- Viewing constraints - Telescope cannot point to closer than 59 degrees to the sun or earth limb.

Those parameters of the telescope and facility having a direct bearing upon observations of solar system bodies are the orbital inclination, the viewing angle constraints, and the tracking of non-sidereal targets.

The nominal orbital inclination of 28.5 degrees permits the observation of solar system objects at and near opposition, and is fully suitable for planetary science needs.

The viewing angle constrains observations to solar elongations of greater than 59 degrees, and thereby eliminates Mercury and Venus. The other major planets are visible for acceptably large time intervals during the year.

The non-sidereal tracking parameter is more than adequate for the major planets, comets at large distances from the Earth, and for all main belt asteroids. In order to evaluate this parameter in terms of Earth-orbit crossing asteroids, which are

of significant and growing interest in planetary science, we have computed the orbital ephemerides and tracking rates of all the known planet-crossing asteroids visible in 1988. There are 26 known Earth-crossers and 48 known Mars crossers, with the likelihood that an additional 10 planet crossers will be discovered during that year. These are the asteroids that have the possibility of the closest approaches to the Earth, with the result that their tracking rates are very high. Of the 74 planet crossers scheduled for 1988, none has a tracking rate that exceeds even half of the SIRTf nominal capability.

Comets occasionally approach the Earth sufficiently closely to have very large tracking rates. Comet IRAS-Araki-Alcock approached so closely that its rate exceeded the SIRTf parameter by a wide margin for a few days. Asteroids are estimated to exceed the SIRTf parameter on the average of one object every two or three years. That is to say, it is a fairly rare occurrence.

Therefore, the non-sidereal tracking rate specified for SIRTf is considered quite adequate for the needs of planetary science.

Other facility parameters of importance to planetary observations with SIRTf include the field of view, image quality, pointing stability, and wavelength coverage of the various instruments. The large field of view of the telescope (7 arcmin) is fully adequate for planetary observations; the diameter of the largest planet (Jupiter) is less than 1 arcmin. Comets are frequently larger than 7 arcmin when they are near the Earth and have developed comae, but most studies of these objects will concentrate on higher spatial resolution with fields of view much less than 7 arcmin. Image quality of the SIRTf telescope is adequate for photometric and spectroscopic studies of solar system bodies. The pointing accuracy is fully adequate for solar system bodies, some of whose positions are known to less accuracy than the system pointing capability.

B. Instruments

Three instruments selected for the SIRTf are as follows:

1. Infrared Array Camera (IRAC) - PI: G. Fazio, SAO
2. Multiband Imaging Photometer for SIRTf (MIPS) - PI: G. Rieke, Univ. of Arizona
3. Infrared Spectrograph (IRS) - PI: J. Houck, Cornell

Considered together, these instruments provide the following range of photometric, imaging, and spectroscopic capability:

a. Photometry with diffraction-limited beams, 2 - 700 micrometers, using broad-band and selectable narrow-band filters. Diffraction-limited beam size (FWHM) = 3 arcsec (wavelength = 10 micrometers).

b. Low-resolution dispersive spectroscopy (resolving power about 100), 4-120 micrometers, using diffraction-limited

apertures and detector arrays sampling as much as one octave of the spectrum simultaneously. The option of extending the short wavelength limit of this instrument to 2.5 micrometers is discussed further below.

c. Moderate-resolution dispersive spectroscopy (resolving power up to 2000, 4-120 micrometers, again using diffraction-limited apertures and detector arrays sampling 50 or more spectral resolution elements. The 120-200 micrometer spectral region will be covered by one spectrograph with a resolving power of 500-1000.

d. Wide field and diffraction-limited imaging, mapping, and surveying at 2.5-200 μm , using arrays with as many as 128 X 128 pixels. A variety of modes will be available which will permit diffraction-limited imaging over most or all of the 7-arcmin field of view at wavelengths between 10 and 120 micrometers, and over a smaller portion of the field at shorter and longer wavelengths.

e. Polarimetric capability for use in conjunction with both the imaging and photometric instrumentation.

V. SIRTf CAPABILITIES FOR SOLAR SYSTEM SCIENCE

A. System Sensitivity for Faint Objects in the Outer Solar System

As an illustration of the sensitivity of SIRTf at spectral resolution 1000 (IRS), 50 and 2 (MIPS), the thermal and reflected solar fluxes from various small bodies in the outer solar system are plotted for wavelengths 2-500 μm in Figure 2. This shows the thermal and reflected sunlight components of the radiation from asteroids, Pluto and Triton, and the nucleus of Comet Halley at 5 AU. There are approximately 25 Trojan asteroids with diameters greater than 100 km. In the main belt of the asteroid system, there are approximately 1000 bodies of diameter 40 km or greater. Not all of these asteroids are of special interest, but representatives of all the major and several minor taxonomic types, and some identified with specific meteorite types, are within range of SIRTf at spectral resolutions suitable for diagnostic compositional studies. Spectral observations with SIRTf will extend the compositional studies into wavelength regions that cannot be studied from ground-based observatories because of atmospheric absorptions. With this high sensitivity of SIRTf and the requirements of the science, we anticipate that much of SIRTf's work on solar system objects will be done at spectroscopic resolution ($R > 50$). Moreover, SIRTf's photometric ($R \approx 2$) capabilities are amply adequate for solar system studies (Figure 2). Thus we give spectroscopic capabilities particular emphasis in the discussion that follows.

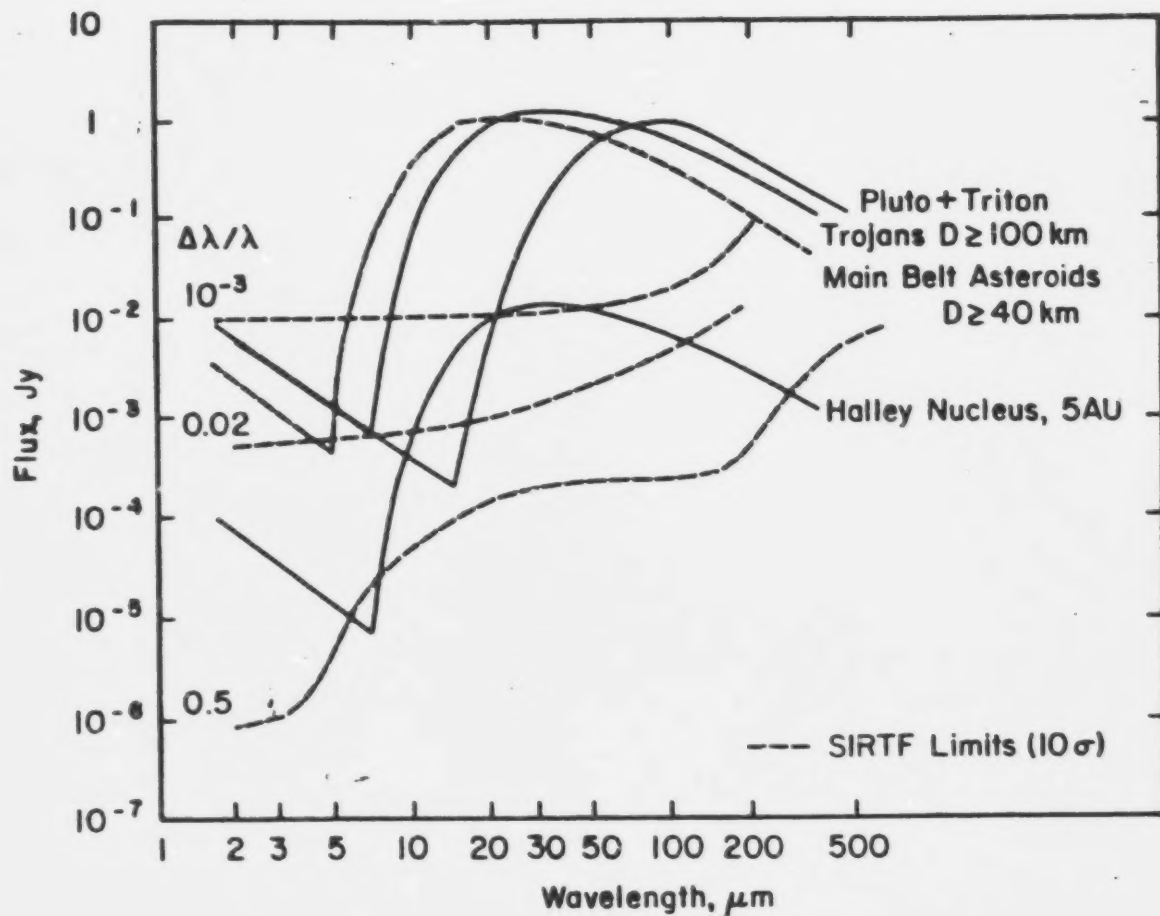
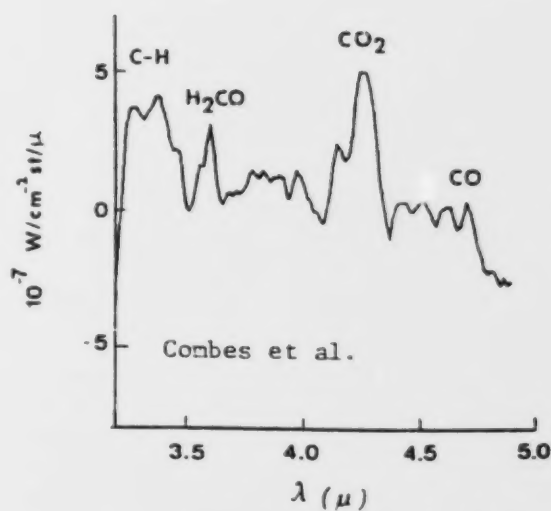
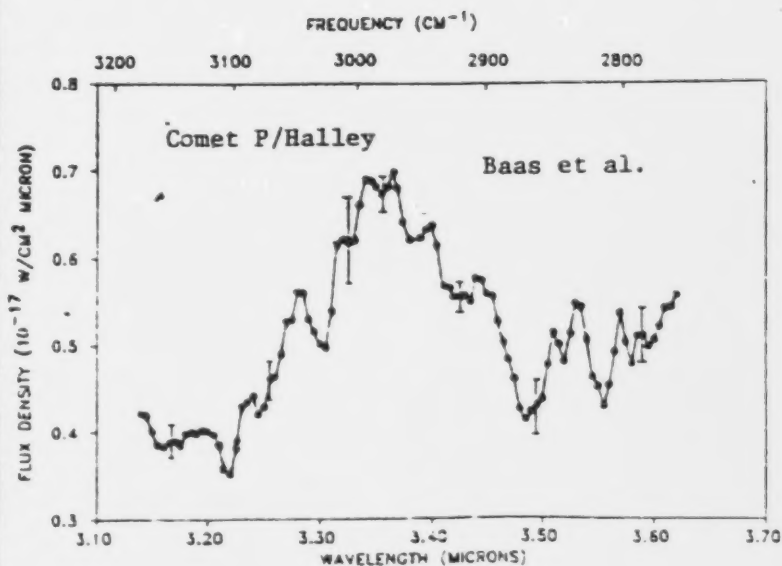


Figure 2. The predicted brightness of various solar system objects in comparison with the SIRTTF 10-sigma measurement limits for 900 sec of integration. The curve for resolution 0.02 is based on the original Infrared Spectrometer proposal; reduced read noise will improve performance at wavelengths shorter than about 5 μm .



Difference spectrum of Comet Halley between scans recorded at nuclear distances of 40000 km and 200000km respectively. Each scan is the sum of 8 individual scans and corresponds to an integration time of 144 s.

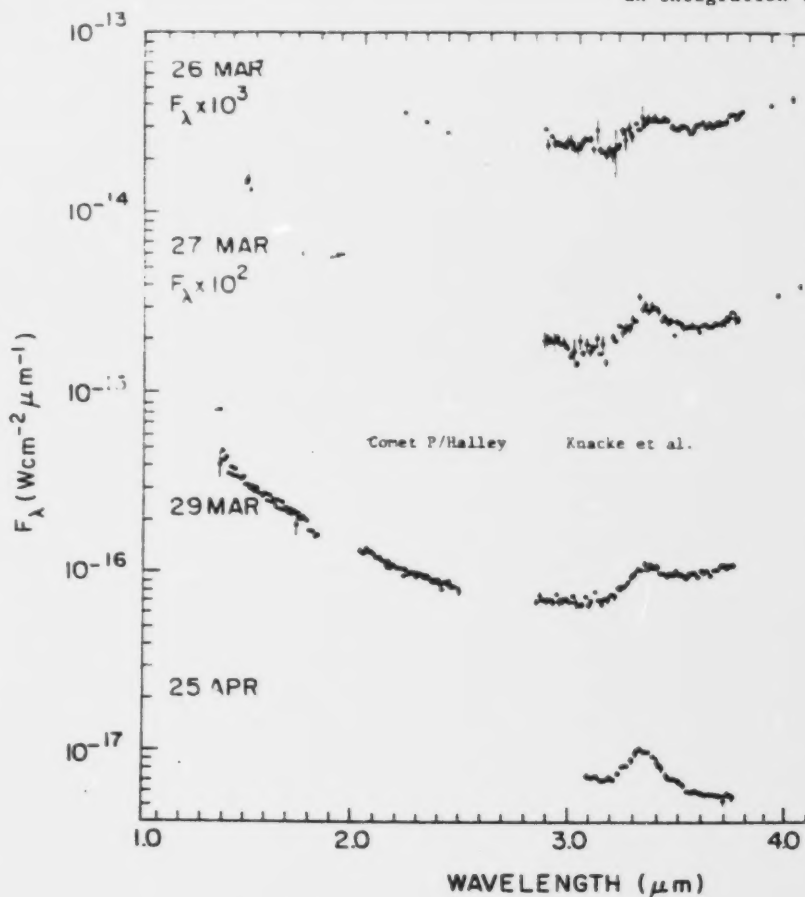


Figure 3. Spectra of Comet P/Halley from various sources as noted.

B. Spectroscopy In The Region 4 to 25 um

The baseline spectral region for the spectrometer on SIRTf has its short wavelength limit at 4 um. Spectroscopy in this region at resolutions afforded by the IRS are expected to be useful in further analysis of mineral and volatile surfaces on small bodies of the solar system, as well as in defining their thermal properties related to regolith development and rotation. The silicate band near 11 um is a diagnostic feature in some solar system bodies, particularly comets. The CO₂ and CO bands in comet P/Halley shown in Figure 3 are the first detections in a comet of these molecules, which are of central interest as parent molecules. Observations of these bands, which are inaccessible from the ground or aircraft altitudes will be of particular interest for Oort cloud comets, as well as for old comets within the inner solar system. In the laboratory, this spectral region has not been thoroughly studied for solid materials such as minerals and ices, but it is of growing interest in the context of organic components of the interstellar medium and related implications for comets. Organics with structures representative of low formation temperatures show extensive spectral features in this region. An enormous body of understanding of organic molecules has been built by chemists through studies in the 4-25 um spectral region.

C. SIRTf and the CRAF Comet

The payload and the investigation teams have been selected for the Comet Rendezvous Asteroid Flyby (CRAF) mission, though a new start has not yet been achieved. Various comet and asteroid target options exist for different new start and launch dates. All the potential target comets are Jupiter-family objects, meaning those periodic comets having aphelia near the orbit of Jupiter. In the discussion below, we have used the nominal mission profile for the CRAF mission.

The nominal mission profile calls for launch in February 1993, flybys of Venus and the Earth for gravitational assists, flyby of asteroid Hestia in January 1995, and rendezvous with comet P/Tempel 2 at aphelion in November, 1996. The spacecraft will remain in orbit with the comet through the end of the mission on December 31, 1999, and during that four-year span will make numerous close approaches (a few km) to the nucleus and excursions along the axis of the tail. A penetrating probe will be launched from the spacecraft to the nucleus.

SIRTf can contribute to the study of Comet P/Tempel 2 or any other target comet during the CRAF mission in numerous ways. SIRTf can accomplish spectroscopy, imagery at IR wavelengths, and photometry of the comet to measure large-scale phenomena at the time the spacecraft is measuring small-scale phenomena *in situ*. Much experience was gained with Comet P/Halley observations from Earth-based facilities simultaneous with spacecraft flybys. Data sets at the two spatial scales achieved by this simultaneity are

the subjects of several current lines of investigation. SIRTf's long lifetime over a range of comet-sun distances as the comet evolves with time will permit such simultaneous observations.

The nominal CRAF mission timeline, the distance of the comet, and the expected fluxes at 3.45 and 50 μm are shown in Figure 4. The infrared flux for this comet were estimated from the visual-region brightness behavior as collated and modelled by Ray Newburn, and from observations of Comet P/Halley during 1985 and 1986. Comet P/Tempel 2 was assumed to be 6 magnitudes fainter than P/Halley for the same distance from the sun (during the active phase). P/Tempel 2 will be observed extensively during the apparition prior to the CRAF mission (perihelion is in September 1988), so that good values of the infrared properties will be available in advance of both the CRAF and SIRTf missions. Similarly, any other selected target comet can be observed in the infrared in advance of the encounter in order to define better the expected fluxes. For planning purposes, the information in Figure 7 should be adequate.

At perihelion and throughout the mission the comet is sufficiently bright to be studied by SIRTf with spectral resolution 100 or better. After the development of the coma, the brightness of P/Tempel 2 will rise sufficiently to permit spectroscopy at the highest resolution of the IRS.

VII. SPECTROSCOPY IN THE REGION 2.5-5 μm

In this section, we make the case for extending the wavelength range of the Infrared Spectrometer (IRS) shortward to 2.5 μm rather than the baseline cutoff at 4 μm .

The spectral region beginning at about 2.5 μm contains diagnostic absorption bands in reflectance spectra of minerals and ices of cosmochemical relevance in planetary studies. Most of the work on the mineralogy of asteroid and planetary satellites and the study of ices on these bodies (plus Mars) has been accomplished in the 0.3-2.5 μm region because of accessibility to ground-based telescopes, but sulfur dioxide ice is observed on Io and carbonates have been sought on Mars out to the 4.2- μm atmospheric cutoff. Laboratory work in the region longward of 2.5 μm on minerals and ices of cosmochemical interest is in its infancy, but is being propelled forward by the near prospect of spacecraft remote sensing reflectance data out to 5.2 μm (Galileo, Mars Observer, CRAF, and Cassini). The goal of the laboratory programs in progress is not only to extend the wavelength beyond the earlier work, but to increase the resolution to 1000-2000. Further, techniques for merging spectral information with image arrays to match data sets expected from spacecraft at other planets and from remote sensing experiments above the Earth are being developed at a few centers.

Figure 5 shows representative laboratory spectra of ices of cosmochemical interest at resolution about 100. Diagnostic features exist throughout the spectral region 2-6 μm ;

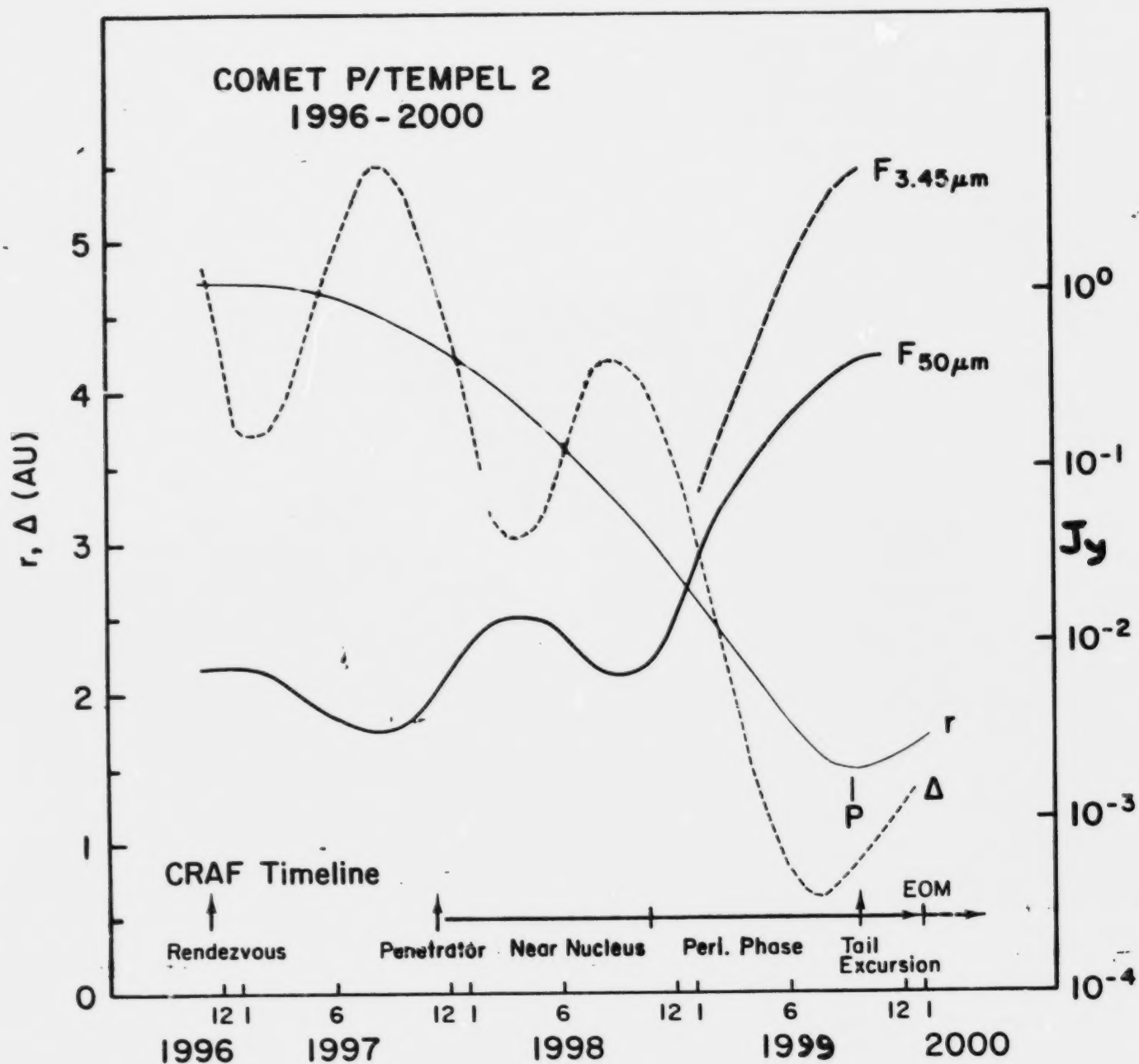


Figure 4. The expected fluxes of the CRAF comet, P/Tempel 2, at 3.45 μm and 50 μm throughout the nominal mission.

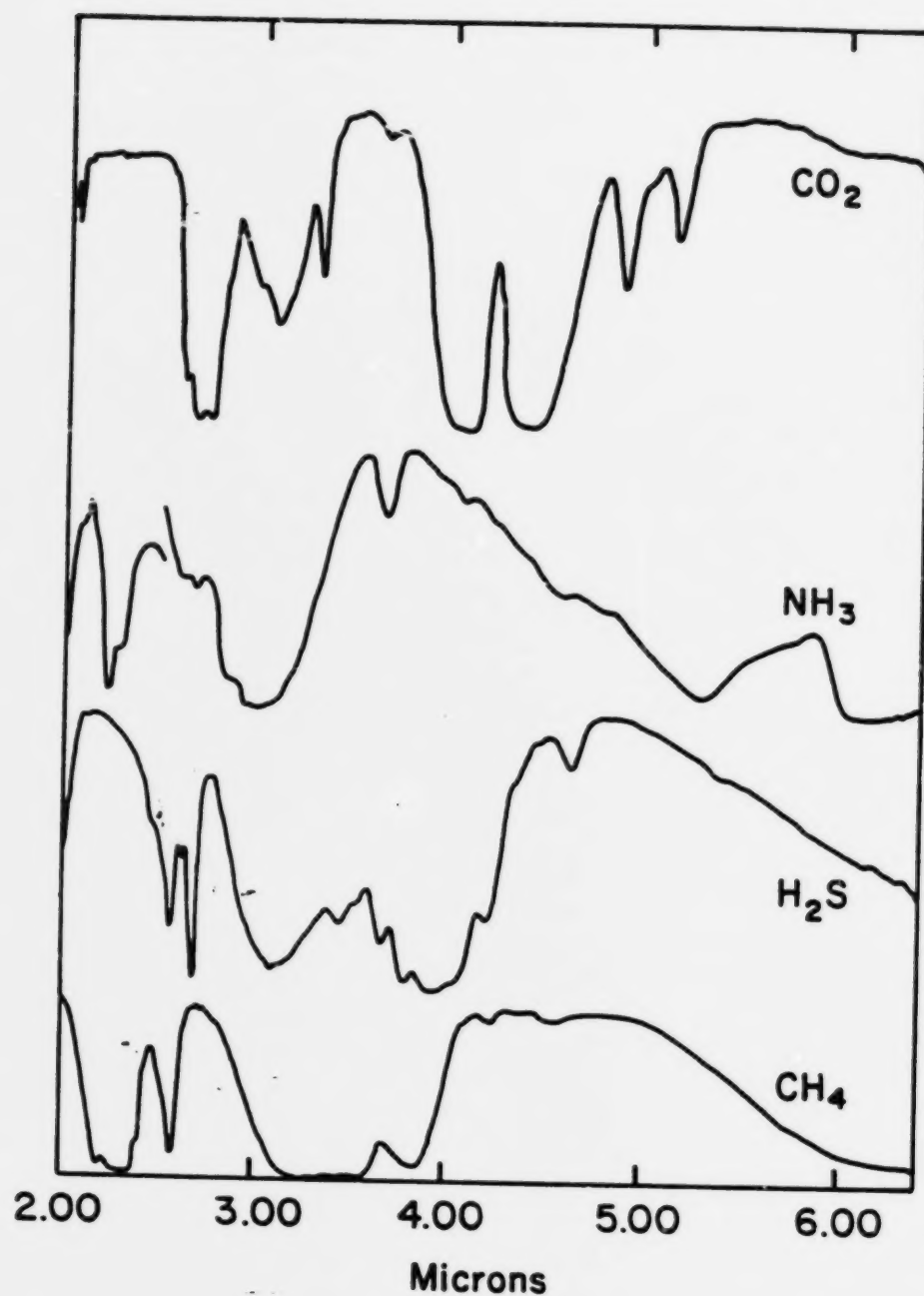


Figure 5. Laboratory reflectance spectra of ices of planetary interest, 2.0-6.0 μm . Unpublished data by H. Kieffer.

at higher resolution, additional features could be expected, but the laboratory data are presently not available. Likewise, in refractory minerals, spectral features of importance are found throughout this region, both at resolution 100 and especially at higher resolution. Figure 6a,b shows new data on minerals at resolution 200-400. Features diagnostic of the state of hydration of certain minerals are important in solar system studies, as are those indicative of new minerals not detectable by spectroscopy at shorter wavelengths where the bands are weaker and overlap one another.

Note that spectral bands can be diagnostic not only of composition or the state of hydration of minerals, but can also serve in some cases to indicate particle sizes and packing densities of solid surfaces. The interpretation of laboratory data in this context is a very new field of study, but the preliminary results are highly promising. Not only can specific absorption bands be used to decipher particles sizes in a monomineralic surface, but a rigorous surface multiple scattering theory is being developed for the interpretation of multi-mineralic surfaces in which the compositions, relative concentrations, particles sizes of each component, and the packing density can be determined. This work, in progress in the laboratory of Dr. R. N. Clark (U.S. Geological Survey, Denver), has shown highly promising results so far, and will become a physical foundation of remote sensing of planetary surfaces with telescopes and spacecraft, as well as in terrestrial settings.

Of central importance is the occurrence and distribution of those spectral features related to organic activity on solid surfaces and in the atmospheres of planets and planetary satellites. In particular, the C-H band complex at 3.4 μm in comets, on asteroids, and on planetary satellites is of considerable importance to issues of the origin of the dark material that is distributed throughout the solar system. The CN band at 4.5-4.6 μm is similarly of great importance, as the combination of the C-H and the CN bands bear directly on questions of the origin and distribution of life in the solar system and elsewhere. A C-H/CN survey of the small bodies of the solar system can only be accomplished with SIRTf because of the difficulties in ground-based measurements of these two band complexes.

SIRTf instrumentation is optimized for spectral regions where the extremely low background radiation from a cryogenic telescope offers the maximum advantage over telescopes at ambient temperature. In order to compare the performance of a ground-based (or other ambient temperature telescope, such as SOFIA at 14 km altitude or HST in earth orbit), T. Herter has computed the projected background noise equivalent flux density at resolution 100 for SIRTf in comparison with HST, SOFIA, and the 10-m Keck Telescope. (See Appendix for details) Figure 7 shows the 1-sigma NEFD versus wavelength for these telescopes in comparison with SIRTf. At wavelengths shorter than about 3 μm for SOFIA and HST, and 3.5 μm for the Keck Telescope, these larger instruments

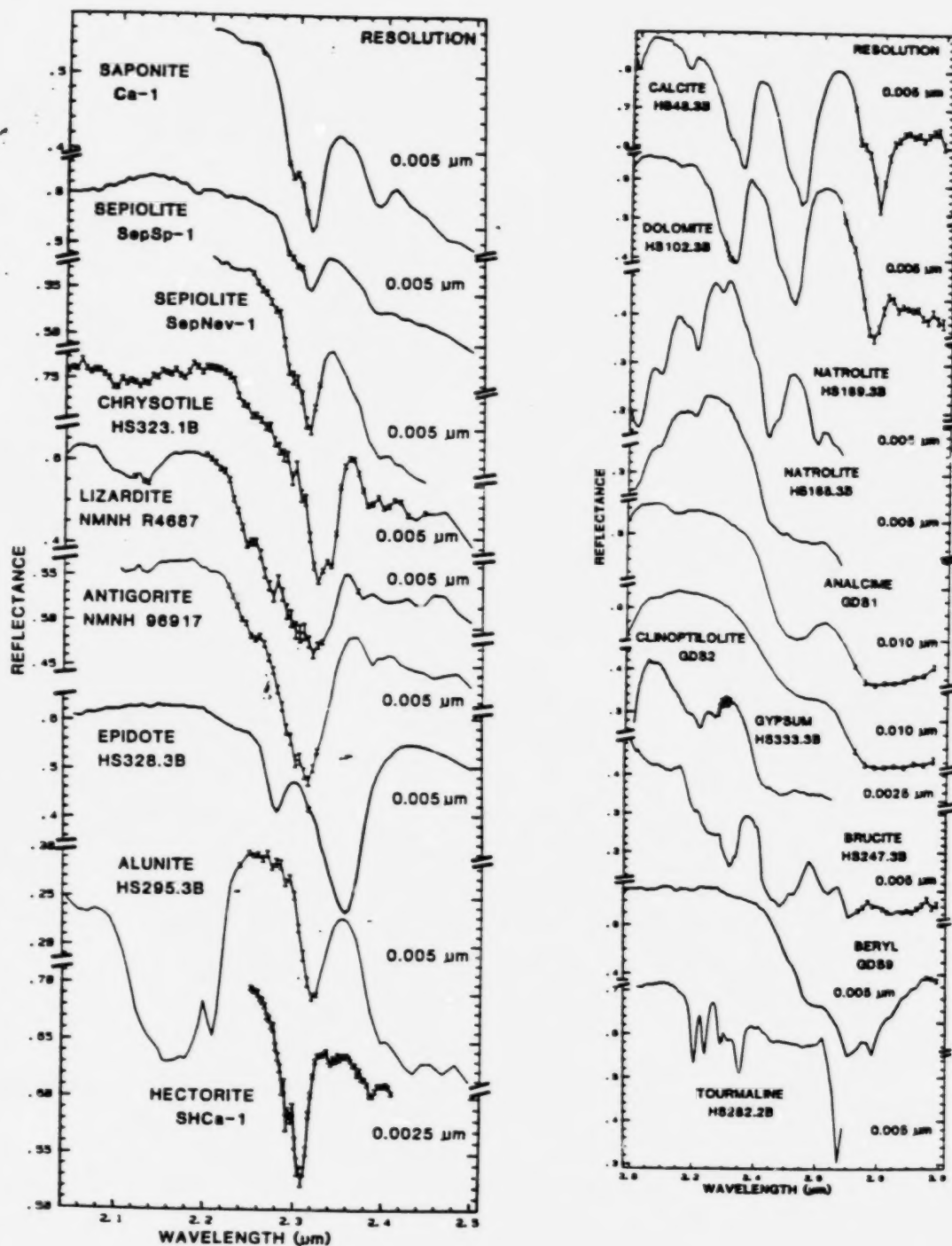


Figure 6 a,b. Laboratory reflectance spectra of minerals of planetary interest, 2-3 μm , at resolutions 200 and 400. From Clark et al., J. Geophys. Res., in press.

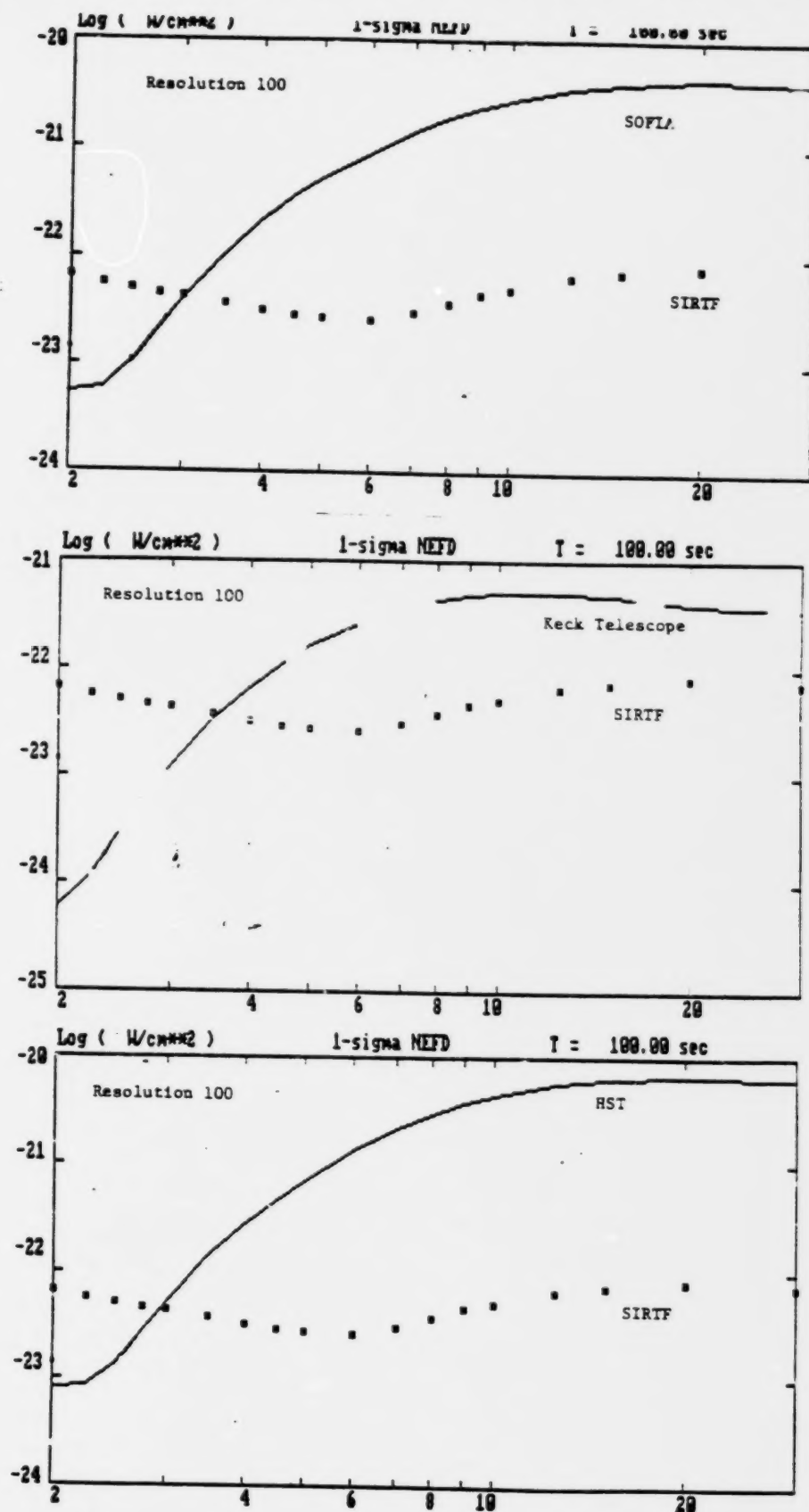


Figure 7. Computations of the sensitivities of SIRTf in comparison with SOFIA, the Keck 10-m telescope, and the Hubble Space Telescope. Those portions of the spectrum unavailable to the Keck telescope are deleted from the curve.

are superior to SIRTf. However, the residual telluric spectrum from Mauna Kea and SOFIA altitudes is sufficiently complex to disturb measurements in some wavelength bands (see below). In addition, the broader wavelength coverage that would be available by an extension of the IRS spectral range to 2.5 μ m would be of great value in numerous observations, and would provide a good wavelength overlap with ground-based data sets.

VII. HIGH-RESOLUTION ($R = 3000 - 100,000$) SPECTROSCOPY WITH SIRTf, 2 - 16 μ m

Low-resolution spectroscopy is suited to the study of minerals and condensed volatiles on planetary surfaces, and for some problems of planetary atmospheres. For this work, the IRS will be extremely valuable, as discussed in a previous section. Low resolution is inadequate for many problems in the study of the atmospheres of the planets, satellites, and comets, however, and in this section we consider issues related to high-resolution ($R = 3000$ to $100,000$) spectroscopy with SIRTf.

Science objectives in cometary and planetary atmospheric studies often require information at the ultimate limit of spectral line resolution. The exact requirement depends upon the linewidth-limiting physics of the medium and upon the information to be extracted. In some cases, this takes the resolution requirement to the intrinsic doppler width of a line formed in a tenuous gas at low pressure, and in other cases the requirement is limited by the limb-to-limb planetary rotation (some few hundred m/sec for resolved spots on Jupiter). Cometary emission lines and narrow lines formed high in planetary stratospheres are among the solar system problems requiring the highest resolution. Applications of fourier transform spectroscopy (FTS) and heterodyne spectroscopy (HS) to planetary problems requiring doppler-limited resolution have been highly productive in recent years. Ground-based telescopes and the Kuiper Airborne Observatory (KAO) have been used in this work

Among the successes of this work are the following:

- A. Detection of previously unsuspected mesospheric emission in the atmospheres of Venus and Mars. The study of this solar-pumped natural laser emission is yielding details of the excitation physics in the mesospheres, as well as mass transport in the high atmospheres of these two planets.
- B. Doppler-limited maps of carbon dioxide on Mars made in one line of the 10.4- μ m band show variations in the surface temperature and pressure, and laser emission from the mesosphere. When modelled, the line profile yields information on the structure of the atmosphere from the surface to the 100-km level. Global maps of the mesospheric temperature reveal poleward warming, and probably atmospheric thermal waves.

C. Observations of individual rotational lines in ethane emission, for example in the stratosphere of Jupiter, are used to probe the physics of the high atmosphere of the planet. The abundance with height can be determined, as well as the temperature-pressure structure over a wide range of height, by modelling the resolved intrinsic line profile.

D. Planetary seismology, an offshoot of helioseismology, is presently being pursued with amplitude-temporal power spectra at thermal infrared wavelengths, seeking to identify waves in planetary atmospheres which will yield information on the convective depth of those atmospheres and on many other presently unknown atmospheric parameters.

E. Direct detection of water vapor has been achieved in the spectrum of Comet Halley from FTS data taken on the KAO. This was possible only at very specific times when the doppler shift from the comet's relative motion moved the lines sufficiently far from the telluric absorption lines still present in the atmosphere at 12 km altitude. The variability of the cometary emissions was measured on time scales of minutes, hours and days, indicating an unexpected degree of heterogeneity on a spatial scale of about 100 m at the nucleus. Full characterization, including kinetic temperatures, velocity fields, ortho-para ratios, and other properties were obtained from these data.

F. Detection and abundance measurements of numerous minor gas species in the atmospheres of the outer planets, are being achieved from both ground-based telescopes and the KAO. The highest resolution is required to separate the weak lines from the strong telluric absorption bands present at the highest ground-based sites and even from the 12-km high KAO.

These examples are offered to show the diversity of investigations of fundamental importance in planetary science which require higher spectral resolution than can be achieved with the selected instrument complement on SIRTf.

The major question arising in connection with the consideration of a high-resolution spectrometer on SIRTf is whether the same work can be done with much larger telescopes from the ground or in airborne observatories.

T. Herter has also provided calculations of the background flux limits at various bandwidths corresponding to spectral resolutions of 3000, and 100,000 for SIRTf in comparison with the Keck 10-m telescope at Mauna Kea, the projected SOFIA 3-m telescope in an aircraft, and with the Hubble Space Telescope. Graphs from the calculations for $R = 3000$ and 100,000 are shown in Figure 8 for each of the three telescopes. (Some details of the calculations are given in the Appendix.)

Figure 8 shows that each of the other telescopes is superior to SIRTf in the short wavelength regions, particularly at the highest resolution. The reason for this is that SIRTf no longer

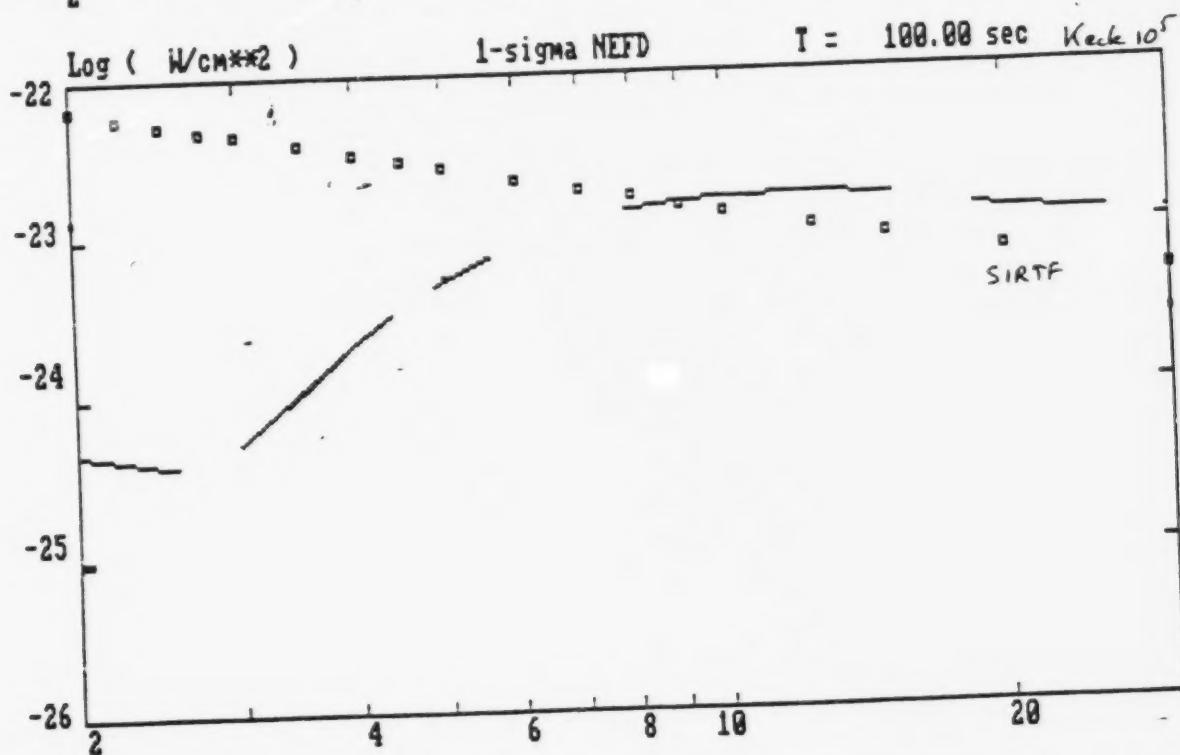
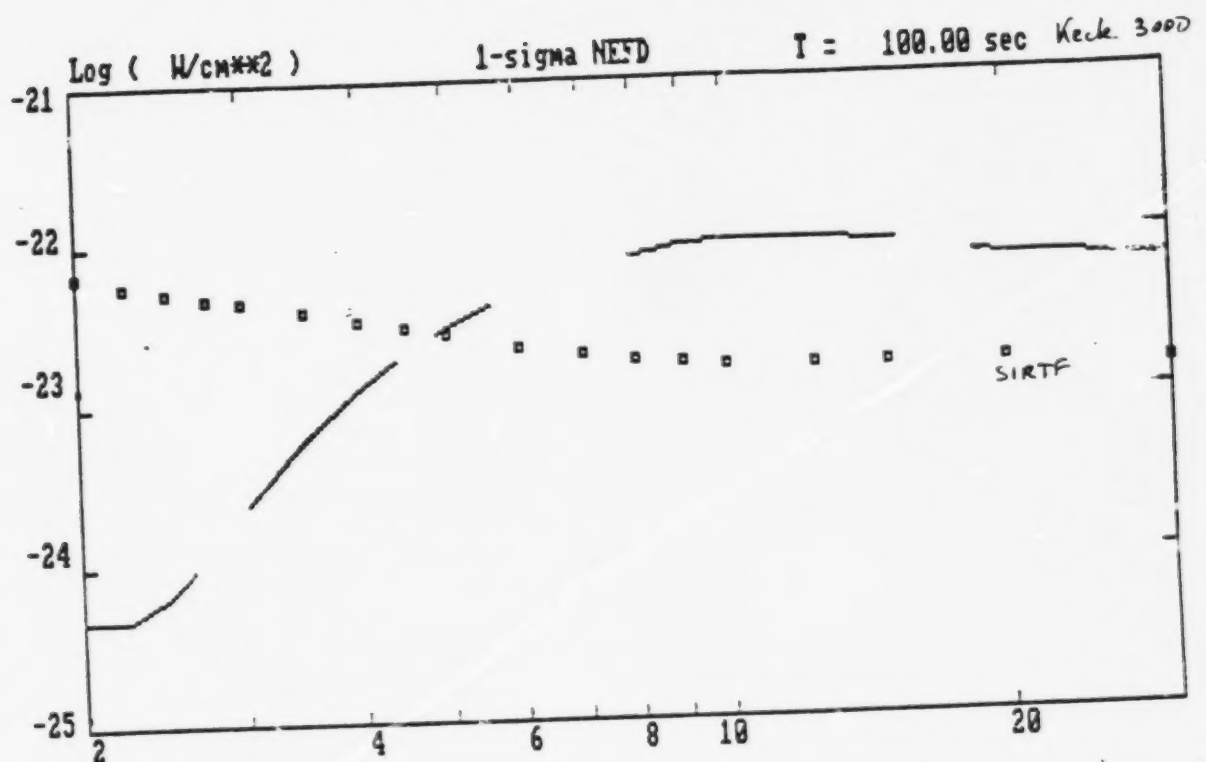
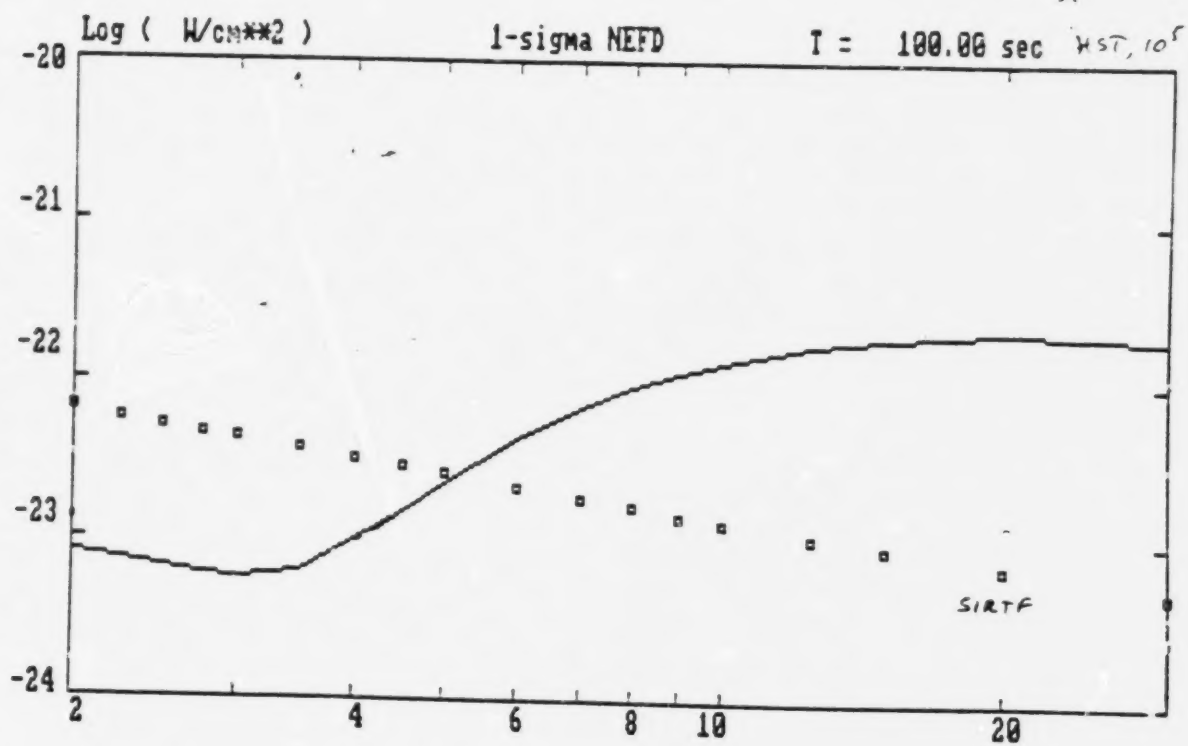
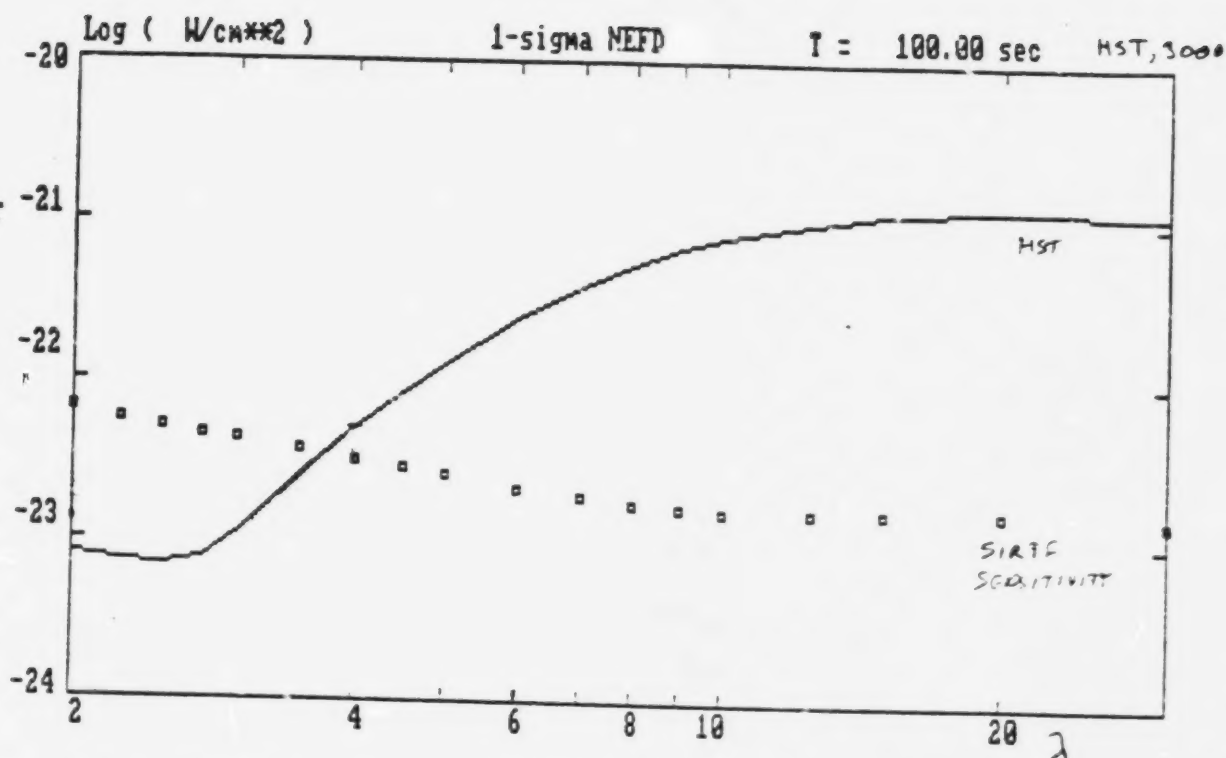
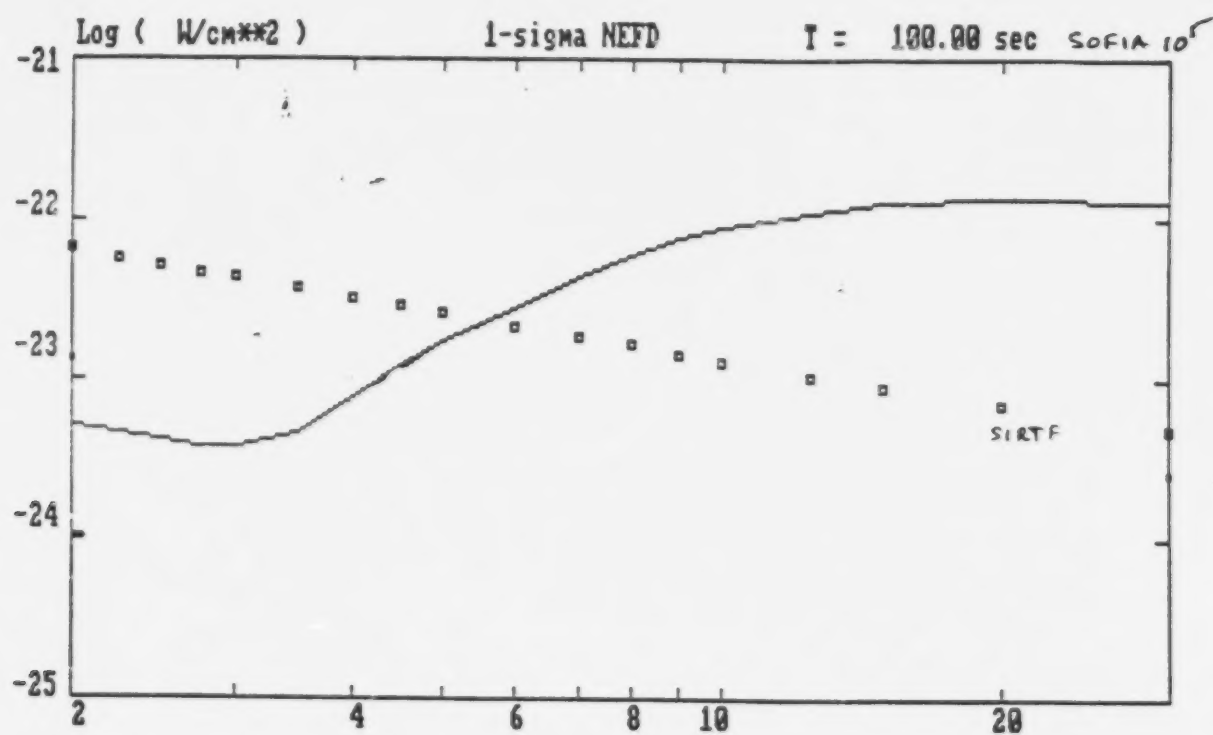
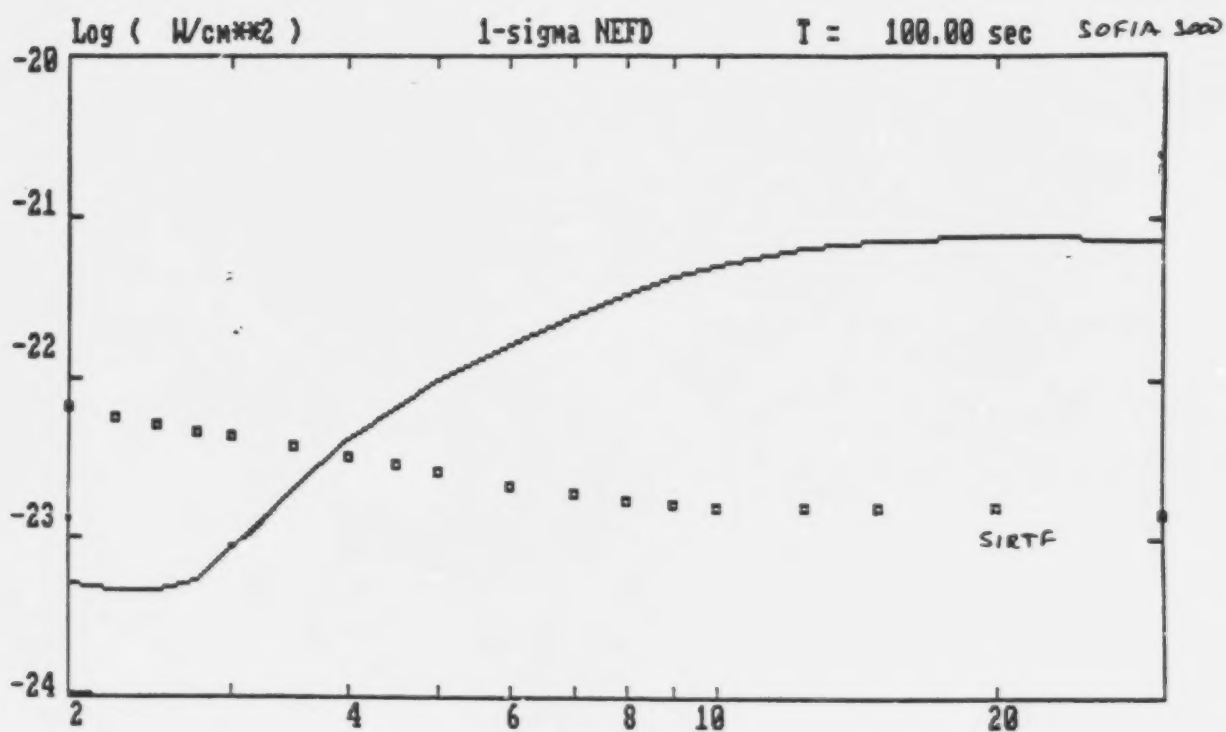


Figure 8 a,b,c. One-sigma NEFD for SIRTTF (open points) and three telescopes (Keck 10-m, Hubble Space Telescope, and SOFIA), shown at two resolutions, 3000 and 100,000. Those portions of the spectrum unavailable to the Keck telescope are deleted from the curve.





achieves background-limited performance at $R = 10^5$, even with the assumed detector performance; by its nature, a very high resolution spectrograph does not fully exploit the capabilities of a cryogenic telescope.

Of the three telescopes considered, only the Keck 10-meter is in the process of being realized; the infrared instrument for HST is in a study phase, as is SOFIA. Short wavelength IR spectroscopy is best done with the three facilities considered in Figure 8, if only the background flux limit is considered. The primary factor then becomes that of the residual atmospheric transmission at high-elevation mountain sites such as Mauna Kea (Keck, elevation 4.2 km) and the stratosphere at the SOFIA altitude of 14 km.

A large body of experience with spectroscopy at ground-based mountain observatories and the KAO allows an evaluation of the residual telluric absorption above these altitudes. Figure 9 shows telluric absorption spectra computed by the SOFIA Project Office for two relevant altitudes. A substantial amount of residual absorption exists in the 2-14 μ m region even at 14 km altitude in this diagram. At high spectral resolution, the situation is significantly worse than shown, because individual lines comprising the bands reach greater absorption depths than does the aggregate. Figure 10 shows additional computations at higher spectral resolution, using the U.S. Standard Atmosphere, for altitudes up to 30 km. In this figure major regions of the spectrum are still heavily absorbed at 20 km altitude.

The effect of resolution can be further demonstrated in high-resolution data obtained with the KAO. In spectra of the Moon taken with an FTS by H. Larson et al., strong residual absorptions persist in regions affected by water and carbon dioxide (Figures 11 and 12). It is in these regions that important information on the nature of comets lies, but it cannot be separated from the telluric features with the precision required to address certain problems that are expected to remain significant for some time to come. Additional minor constituents of planetary atmospheres are expected in these confused regions of the spectrum, and important information on the temperature-pressure structures of planetary atmospheres is obscured by telluric interference. Isotopic lines, only slightly shifted from the natural lines, are further confused by residual telluric lines, even if the latter are very weak. The study of planetary atmospheres in the ways already described, plus the detection and measurement of crucially important cometary lines depends upon high spectral resolution in spectral regions clear of telluric interference. This can be accomplished only with a telescope in space.

The infrared instrument proposed for the Hubble Space Telescope will be installed in the first refurbishment. The schedule for the refurbishment mission is unknown, or at least subject to large uncertainty. Furthermore, the instrument has not been selected from two competing proposals, but neither of

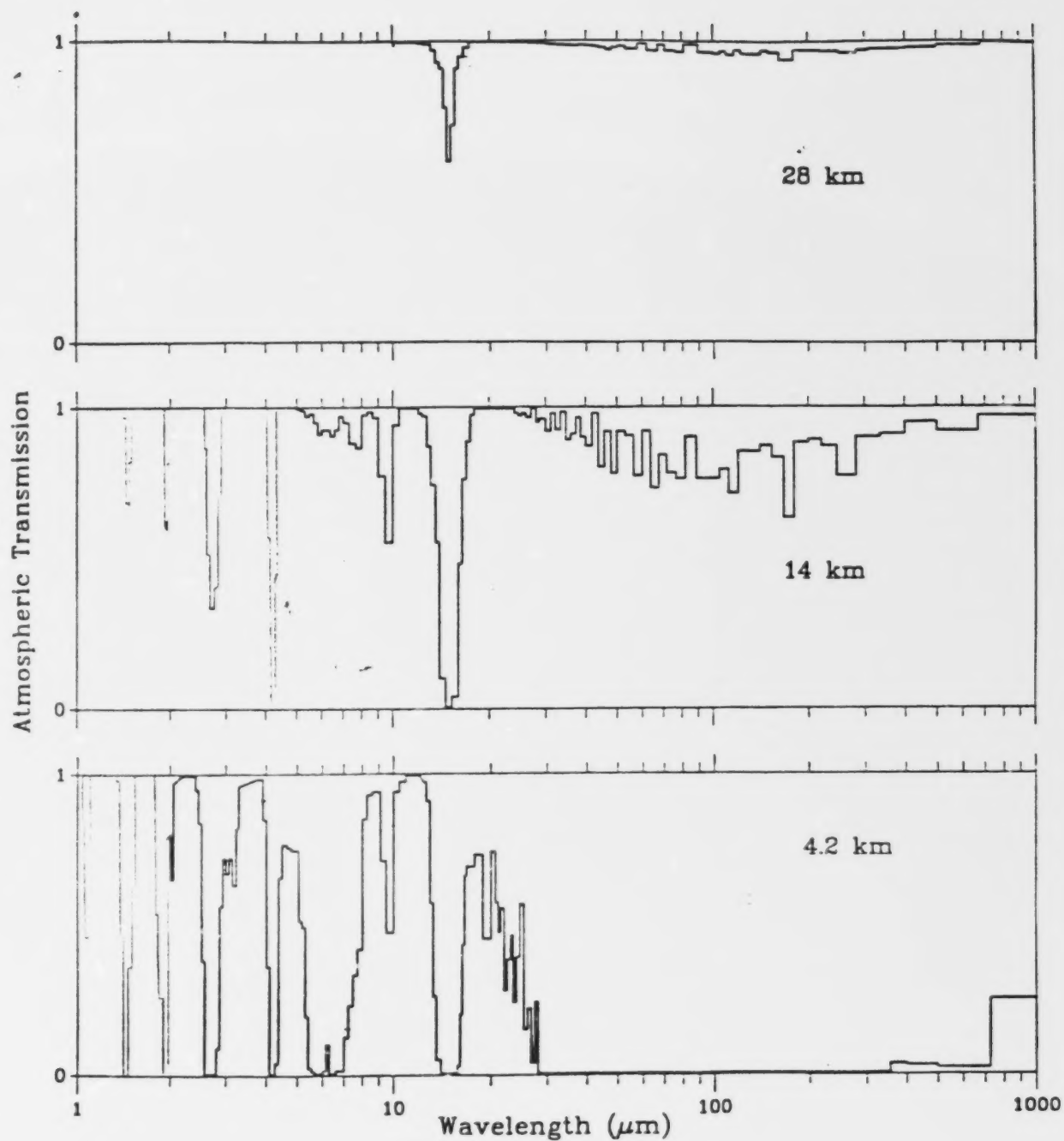


Figure 9. Transmission of the Earth's atmosphere at various altitudes, from computations using the U.S. Standard Atmosphere.

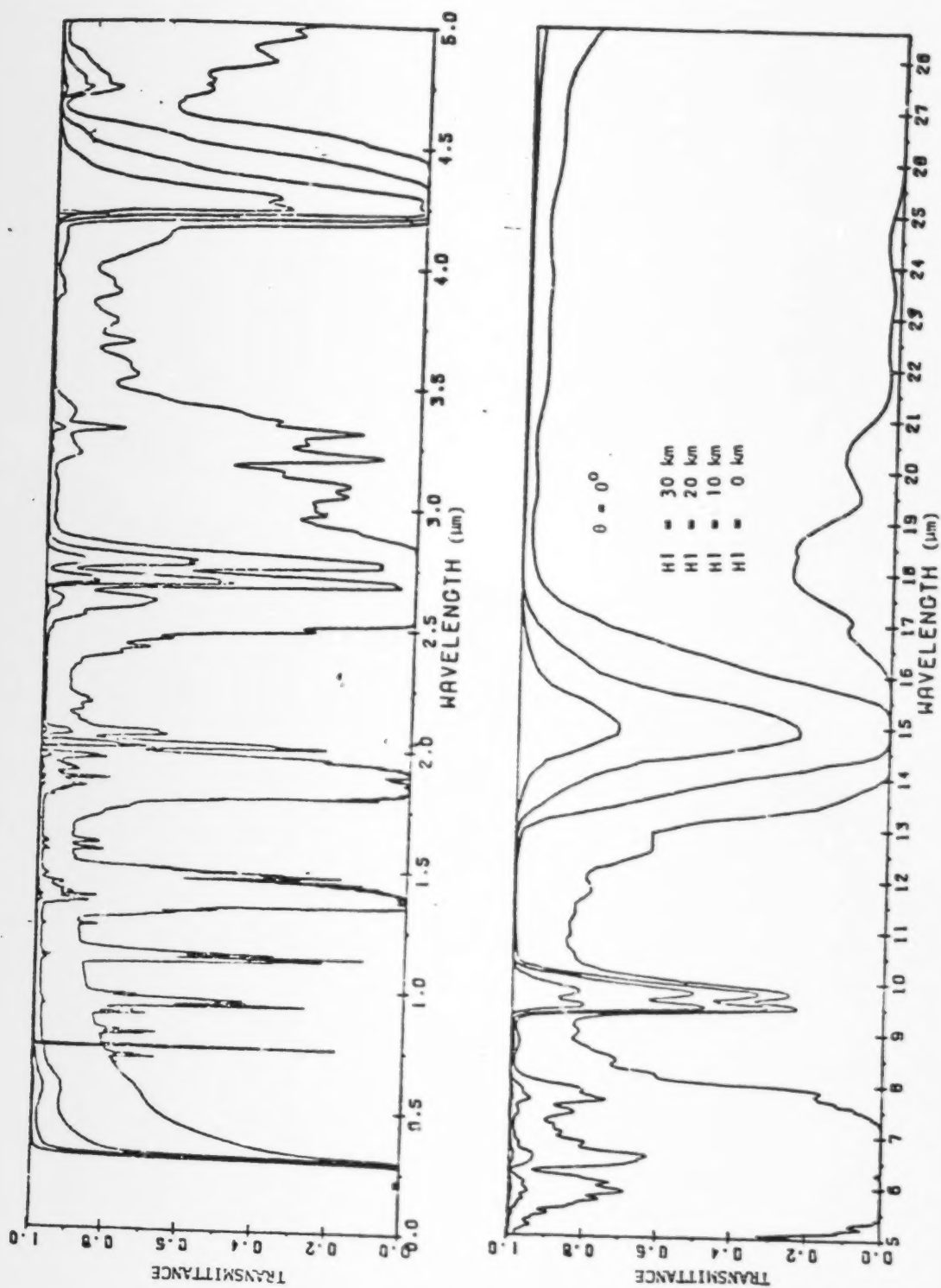


Figure 10. Transmission of the Earth's atmosphere at various altitudes, from computations using the U.S. Standard Atmosphere

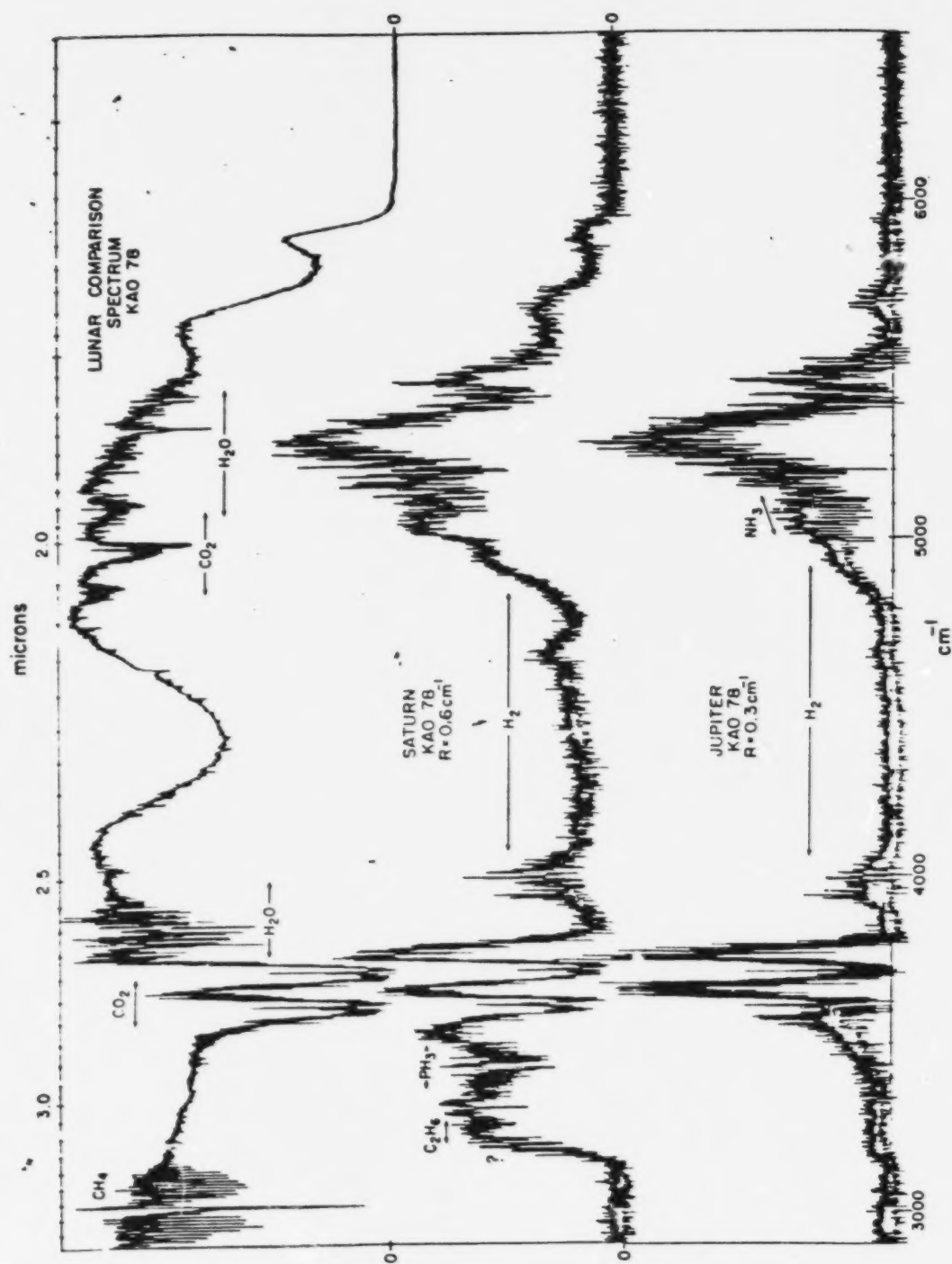


Figure 11. Comparison of the spectra of Jupiter and Saturn in the 2-3 μ m region. A Fourier spectrometer was used on the Kuiper Airborne Observatory to record these data. The lunar comparison spectrum indicates instrumental response and telluric absorptions for the planetary observations. These are the only high resolution observations of either planet that provide continuous spectral coverage in this wavelength region.

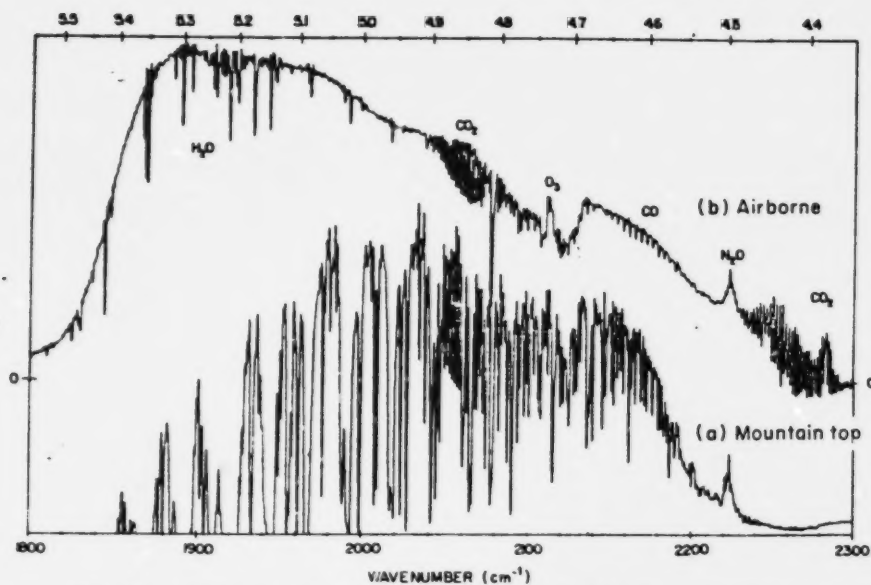


Fig. 12. Lunar spectrum at the $5\ \mu\text{m}$ atmospheric window from (a) a mountain top observatory (Catalina Observatory near Tucson, 1.5 m telescope) at an altitude of 2.5 km and (b) the Kuiper Airborne Observatory (0.9 m instrument) flying above the tropopause at an altitude of 12.6 km. The ground-based spectrum is dominated by strong water vapor absorptions, while at aircraft altitudes only a few water lines remain in addition to some lines due to CO_2 , O_3 , CO , and N_2O in our atmosphere.

the two candidates offers spectral resolution greater than about $R = 3000$, and is confined to wavelengths $< 2.5 \mu\text{m}$. The only prospect for a high-resolution spectrometer in space is that of an additional instrument on SIRTf.

VIII. RECOMMENDATIONS

The SIRTf Science Working Group and the Project Office have demonstrated their serious interest in ensuring that SIRTf will offer planetary scientists a valuable tool for extending our knowledge of our own solar system and extra-solar planetary systems. To this end, certain choices of facility, telescope and instrumentation parameters have already been made with the needs of planetary scientists in mind. The baseline SIRTf described above will be a very powerful instrument for planetary science. In the spirit of the cooperation already evinced, the following recommendations for the further enhancement of SIRTf for planetary science are offered:

A. This report recommends that the short wavelength limit of the IRS be extended to $2.5 \mu\text{m}$ in the low-resolution mode in order to achieve various goals in planetary studies, as outlined above. This is a superior and less costly solution than the inclusion of a separate low-resolution, short wavelength spectrometer.

B. Major achievements in planetary science can be expected from the continued exploitation of the power of high-resolution spectroscopy from large earth-based telescopes and from the KAO and its successor, SOFIA. Some problems of major significance in planetary science require high-resolution spectra from space, because of the residual telluric atmosphere even at stratospheric altitudes.

This report recommends that the SIRTf Science Working Group endorse a plan in which the inclusion of a high-resolution spectrometer in the SIRTf instrument complement be studied by the Project and by NASA Headquarters.

IX. ACKNOWLEDGMENTS

This report draws upon material prepared by F. Witteborn, M. W. Werner, L. Lebofsky, M. Sykes, J. Lunine, M. Mumma, D. Tholen, R. A. Brown, T. Herter, A. T. Tokunaga, R. Knacke, and others.

February 18, 1988

Appendix

T. Herter provided computations of the projected noise equivalent flux density at resolution 100, 3000, and 100,000 for SIRTf in comparison with HST, SOFIA, and the 10-m Keck telescope. The assumed detector read noise is 50 e⁻, and the integration time is 100 sec. The 1-sigma NEFD versus wavelength for these telescopes in comparison with SIRTf at resolution 100 is shown in the three panels of Figure 7, and for higher resolutions in Figures 8. Realistic instrumental parameters and backgrounds have been assumed; the field of view diameter assumed is the greater of 1 arcsec or $2.4 \lambda/D$.

Future detector developments could reduce the read noise to about 10 e⁻ and may improve the capabilities for long integrations.